TOWARDS MAPPING THE OCEAN SUFRACE TOPOGRAPHY AT 1 KM RESOLUTION

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ABSTRACT

We propose to apply the technique of synthetic aperture radar interferometry to the measurement of ocean surface topography at spatial resolution approaching 1 km. The measurement will have wide ranging applications in oceanography, hydrology, and marine geophysics. The oceanographic and related societal applications are briefly discussed in the paper. To meet the requirements for oceanographic applications, the instrument must be flown in an orbit with proper sampling of ocean tides.

1. INTRODUCTION

Since Seasat we have realized the wealth of information in the details of the map of the surface topography of the ocean. Despite the revolutionary impact of radar altimetry achieved over the past quarter century, its sampling capability has always been a compromise between the spatial and temporal requirements. As a result, high spatial resolution can only be achieved in the along-track direction, leading to asymmetry in the radar's mapping capability. For example, the zonal currents of the ocean tend to be better determined than the meridional currents, and the meridional gravity anomalies tend to be better determined than the zonal anomalies (Figure 1).

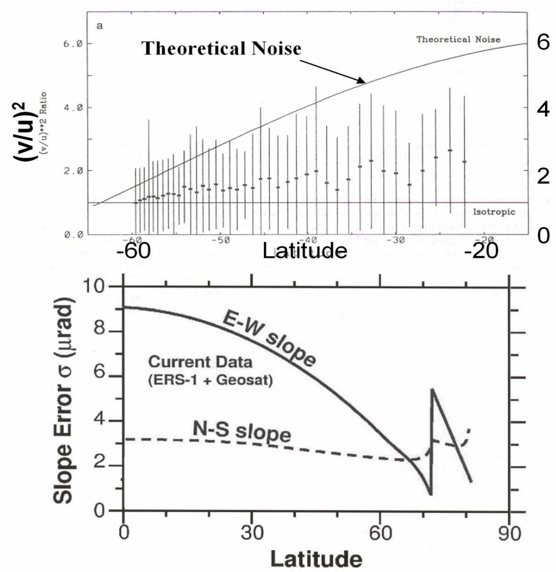

Figure 1. Upper panel: The ratio of north-south velocity variance to the east-west velocity variance estimated from Geosat altimeter data (Morrow et al., 1994). The "theoretical noise" indicates the amplification of the error in the north-south component of velocity resulting from the orbit inclination. Lower panel: Errors in the measurement of sea surface slope (proportional to gravity anomaly) from the combination of various altimeter data (Sandwell et al., 2001)

A new technology has been demonstrated by the Shuttle Radar Topography Mission (SRTM) for mapping the earth's land topography using the technique of radar interferometry (Farr and Kobrick, 2000). The same technique has been developed for measuring ocean surface topography over a finite swath (Fu and Rodriguez, 2004; Fu, 2003). The instrument was called Wide Swath Ocean Altimeter (WSOA). With a swath width of 200 km, WSOA is able to cover most of the earth in a ten-day repeat orbit with only small holes with no data at mid and low latitudes. The spatial resolution achievable is 15 km with an instrument error of 2-3 cm. The spatial resolution is primarily limited by the along-track resolution due to the finite size of the radar antenna. This limitation can be alleviated by using the technique of synthetic aperture and the spatial resolution can be improved to the level of 1 km. The basic concept of such an instrument and the potential oceanographic applications are discussed in the paper.

2. A SYNTHETIC APERTURE INTERFEROMETRY SYSTEM

The instrument we propose, dubbed the Hydrosphere Mapper (HM) at present, is a direct descendant of the WSOA concept. Figure 2 presents a conceptual instrument configuration. In the following paragraphs, we briefly describe the basis for the interferometric measurements.

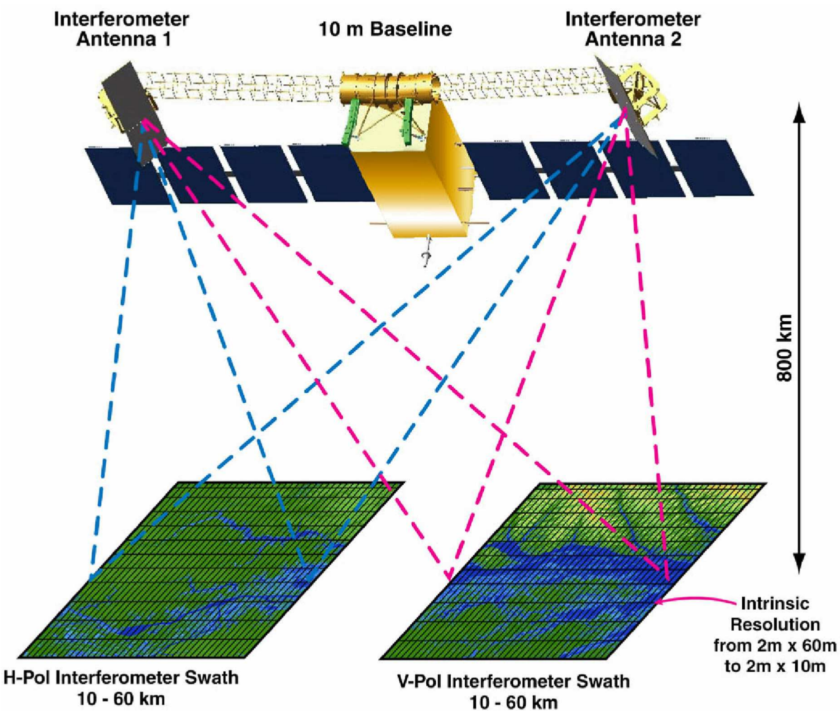

Figure 2. The configuration of the Hydrosphere Mapper

Conventional altimetry is a ranging measurement with cross-track resolution limited by the coarse ground-track spacing. These limitations can be overcome by the introduction of a second antenna to achieve triangulation by measuring the phase difference between the radar channels (Rodriguez and Martin, 1992; Rosen et al., 2000), a technique called synthetic aperture radar interferometry (IFSAR). This technique is quite mature and has been demonstrated by airborne platforms, and, most notably by SRTM, which had two IFSARs (at C and X-bands) that produced global data with an accuracy of a few meters.

In order to achieve centimetric accuracies over water, the radar look angle must be much reduced from the range of 20^{o}-60^{o} for SRTM to about 4.3^{o}. The reduction in look angles entails a reduction in swath, from 220 km for SRTM, to about 50 km (from 10 km to 60 km in cross-track distance), for HM. In order to mitigate this loss in coverage, we look to both sides of the nadir track to achieve a total swath of 120 km. Figure 3 shows the coverage of the North Atlantic Ocean when HM is flown in a 16-day repeat orbit. Small holes of missing data (of dimension less than 100 km) exist only at low latitudes with more than one sampling per repeat cycle at mid and high latitudes.

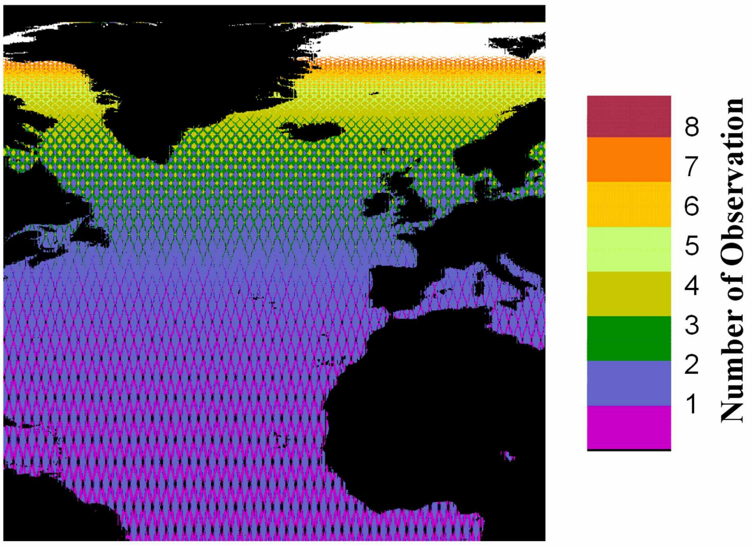

Figure 3. The coverage of HM in a 16-day repeat orbit.

The height noise of the instrument is proportional to the ratio between the electromagnetic wavelength (λ) and the interferometric baseline (B). For SRTM, a 63 m baseline was required to achieve the desired height accuracy using a wavelength of 5.6 cm (λ/B~8.9×10^{-4}). Such a large structure entails large costs. In order to reduce the instrument size, we choose a smaller wavelength (Ka-band, λ=0.86 cm), and reduce the interferometric mast size to 10 m (λ/B~8.6×10^{-4}). Another advantage of Ka band is the small effects of the ionosphere in the radar signal delay. The technology for a 10 m interferometric mast capable of meeting the stringent mechanical stability required for centimetric measurements has been developed in support of the WSOA technology development.

Height noise can be reduced by averaging neighboring image pixels. In order to achieve centimetric height noise, and also in order to produce images of the water bodies, one must increase the intrinsic range resolution of the instrument. We choose a 200 MHz bandwidth system (0.75 m range resolution) to achieve ground resolutions varying from about 10 m in the far swath to about 70 m in the near swath. We achieve a resolution of about 5 m (after onboard data reduction) in the along track direction by means of synthetic aperture processing. After spatial averaging of a large number of pixels, we can achieve centimetric precision at 1 km resolution, which is less than the smallest eddy scales in the ocean by an order of magnitude. For the first time, ocean eddies which account for 90 % of the kinetic energy of the ocean can be fully resolved from space. This new measurement will enable the calculation of ocean surface currents and marine gravity anomalies with much improved accuracies. It can also be applied to mapping the elevation of water surface on land as well as the free board of sea ice and elevation of land ice. The application to oceanography and related societal benefits are briefly discussed in the next section.

3. OCEANOGRAPHIC AND SOCIETAL APPLICATIONS

3.1 Mesoscale Processes

The conventional nadir altimeter measurement has a noise level that limits the detection of ocean sea surface height anomalies (SSHA) at wavelengths larger than about 50 km (Figure 4). The measurement noise of HM is expected to reach a level of 2 cm at a

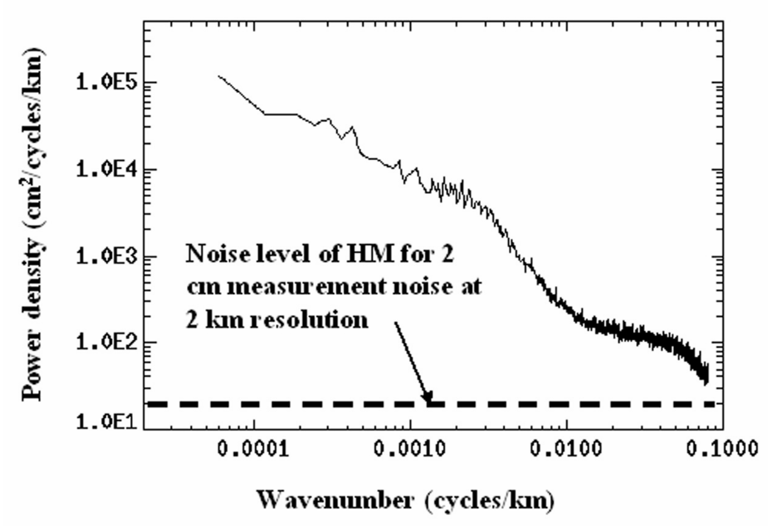

Figure 4. The along-track wavenumber spectrum of SSHA estimated from the Jason altimeter data (solid curve). The dashed line shows the spectral level of the measurement noise of HM.

resolution of 2 km. The spectral level of the noise is almost an order of magnitude less than that of Jason (Figure 4). This measurement performance will allow the detection of SSHA signals at wavelengths shorter than 50 km. Processes at these scales are key to the understanding of the dissipation of ocean eddies and hence the understanding of the time scales of the ocean's role in regulating climate change. The measurement noise of the conventional altimeter also creates significant errors in calculating the ocean surface current velocity (Stammer, 1997). HM will then enable more precise calculation of the ocean surface current velocities.

3.2 Coastal Ocean Currents and Tides

The coarse cross-track resolution as well as the land contamination of the footprint of conventional altimeter measurement has limited the utility of the observations for the study and monitoring of coastal ocean currents and tides. Figure 5 displays the complexity and richness of scales of coastal oceanic processes. The Tandem Mission of TOPEX/Poseidon (T/P) and Jason, with optimal phasing of the two satellite orbits for sampling, is not able to resolve the small scales of the upwelling processes off the coast of California. Even smaller eddies are ubiquitous in high-resolution SAR images of coastal oceans. HM will provide the first observations with adequate spatial resolution for the global coastal oceans that affect about 40 % of the world's population.

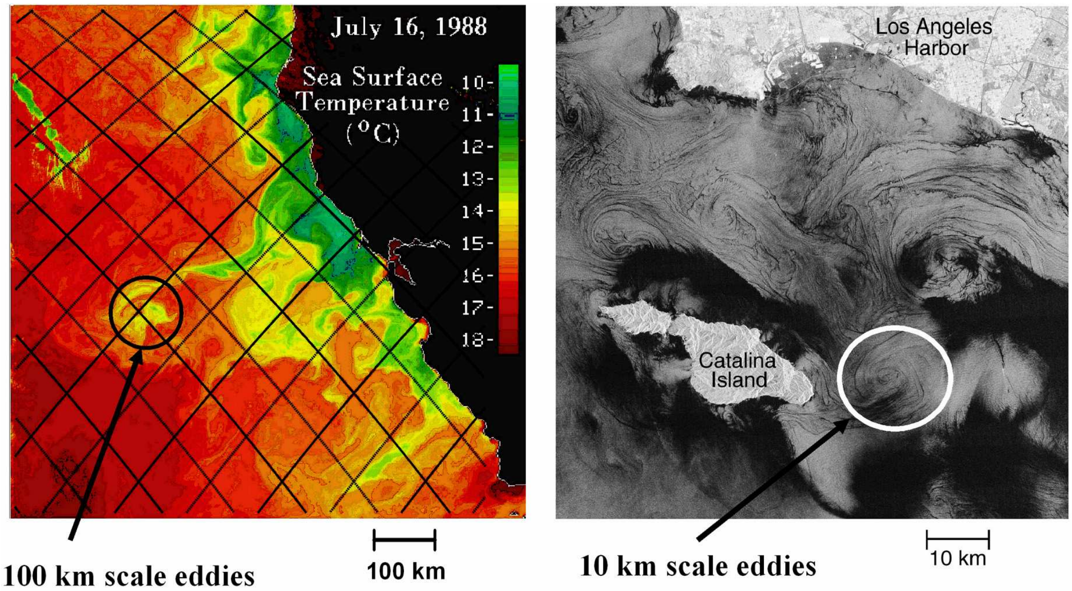

Figure 5. Left panel: Sea surface temperature observed by a satellite infrared radiometer off the coast of California overlaid with the ground tracks of the T/P-Jason Tandem Mission, showing 100-km scale ocean eddies. Right panel: SAR image made by RADARSAT south of Los Angeles, showing 10-km scale ocean eddies.

The spatial scales of ocean tides are smaller in the coastal ocean than the open ocean. The T/P- Jason Tandem Mission data have shown that the tidal height errors in many coastal tide models are as large as 20 cm. If not removed from the altimeter data, the tidal signals will contaminate the observations of low-frequency ocean current variability and mean circulation. The high spatial resolution of HM will make significant advance in improving the knowledge of coastal ocean tides. The knowledge will also allow the removal of tidal errors in the existing decade-long altimeter data in the world's coastal oceans. However, in order to sample ocean tides, HM must be flown in a proper orbit which will not alias the tidal signals to undesirable frequencies (e.g., Parke et al, 1987).

3.3 Internal Ocean Tides

The observations of both surface and internal tides made by T/P have fundamentally advanced the understanding of the source of energy for mixing of the deep ocean (Egbert and Ray, 2001). Approximately 30% of the total tidal dissipation is proven to take place in the deep ocean. The generation of internal tides by surface tides over rough ocean topography is considered a main mechanism for the transfer of tidal energy to the mixing of the deep ocean. The spatial scales of internal tides (Figure 6) are on the order of 100 km which is not well resolved even by the Tandem Mission of T/P and Jason. HM will have the resolution to fully resolve the details of the distribution of internal tide energy.

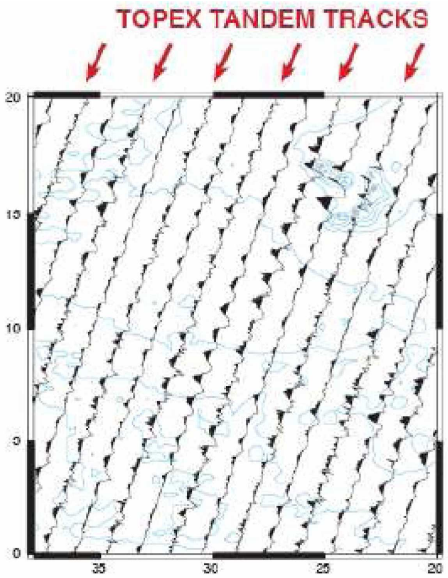

Figure 6. Observations of internal tides along the T/P-Jason Tandem Mission ground tracks, showing the 2-5 cm signals with 100-km scales. (R. Ray, Personal communication)

The sea surface height signals of internal tides, on the order of 2-5 cm over a distance of 100 km, will create a source of errors of 2-5 cm/sec in estimating ocean surface geostrophic velocity at mid latitudes if not corrected in the sea surface height observations. Therefore it is also important to fly HM in a proper orbit to avoid the aliasing of internal tides into low-frequency ocean variability.

3.4 Biogeochemical Processes

Measurements of ocean color from space have revealed complex patterns at mesoscales (Glover, 2001). At these scales, ocean color variability is modulated by physical processes either directly by turbulent advection and stirring or indirectly via impacts on phytoplankton growth rates and trophic interactions. The pattern of the underlying biogeochimcal processes exhibits latitudinal variation with maximal values of 250-300 km along the Equator. The scale decreases poleward to less than 50 km near the poles. The latitudinal decrease in biological spatial scales is similar to the latitudinal variation of the scales of mesoscale eddy motions, suggesting that the mesoscale eddies play an important roles in determining the biological variability. The high-resolution, eddy-resolving observations thus have important applications to the study of biogeochemical processes.

3.5 Hurricane Forecast

The observation of SSHA has been used with models in computing the “heat potential” for the prediction of the intensity of hurricanes. The spatial structure of a hurricane is complex, requiring high-resolution observations. Existing studies, based on the merging of multiple satellite altimeter observations, have shown improvement in the 96 hour lead-time forecast of hurricane intentisty. NOAA’s National Hurricane Center is now routinely using altimeter data for hurricane forecast, but the resolution of the data is likely to decrease due to the lack of multiple altimeter missions in the future. HM will demonstrate making high-resolution measurements with a single spacecraft for hurricane studies and prediction.

3.6 Offshore Operations and Navigation

High-resolution SSHA data, obtained from multiple satellites, have been used by many offshore operations. A notable example is the information on the eddy currents in the Gulf of Mexico. This information has been used by marine operators in scheduling offshore drilling operations with significant cost savings. Information on the surface currents has also been useful for aiding ship routing and yacht racing. More information on this application can be found at
http://wwwccar.colorado.edu/~altimetry/applications/offshore/index.html

3.7 Fisheries Management

The fishery industry is using SSHA data to locate likely places of higher fish concentrations and also to pinpoint locations of target species (e.g., see http://sealevel.jpl.nasa.gov/science/swordfish.html). Fishery managers have used multiple-satellite data in conjunction with other remotely sensed data sets in their planning and coordination. Spatial resolution is a key issue regarding the utility of the observations. HM will make headways in this application.

4. SUMMARY AND DISCUSSION

A new instrument has been proposed to make measurement of ocean surface topography at a spatial resolution approaching 1 km. It will utilize the technique of synthetic aperture radar interferomety with rich heritage from SRTM and WSOA. The measurement will have wide ranging applications in oceanography, hydrology, and marine geophysics. The oceanographic and related societal applications are briefly discussed in the paper. To meet the requirements for oceanographic applications, the instrument must be flown in an orbit with proper sampling of ocean tides. Despite the intrinsic values of tidal knowledge to science and societal benefits, the tides, if not accurately determined and removed from the observations, could be a serious source for errors in the measurement of low-frequency ocean variability and mean circulation. This requirement leads to the avoidance of Sun-synchronous orbits.

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